SELECTION OF MATERIALS IN MINIMUM WEIGHT DESIGN

William R. Micks

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ABSTRACT

This paper discusses how the selection of materials is related to the over-all process of minimum weight design. Examples are given to illustrate the process and to show the necessity for basing materials comparisons on the proper design parameters.

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William R. Micks*

The RAND Corporation, Santa Monica, California

INTRODUCTION

One of the most important parts of the design process is the choice of materials. Generally there are a number of materials to choose from for use in a given design application, and the problem is that of selection among possible alternates.

In simple cases, where one material might serve the function about as well as another, the choice might be based entirely on material and fabrication costs. However, in situations where there is a premium on minimizing weight, the methods of design and material selection become more complex, particularly when the component being designed must satisfy a number of different requirements.

The purpose of this paper is to demonstrate how minimum-weight design methods assist in the selection of materials.

The area of design discussed here deals with structural or load-carrying components. The principles apply to all components having the design function of transmitting forces through space, including such items as jet engines, submarines, bridges, etc.

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Some elementary structural components will be used to demonstrate the use of minimum-weight design methods, and then the more complex design problems will be discussed.

There are three main points that will be covered, and these might be summarized now to indicate the route of the discussion.

The first point to be made is that in comparing different materials for a given type of job, it is necessary that the parameters to be used as a basis of comparison are the correct design (as opposed to analysis) parameters--otherwise the comparison can be misleading. Examples will be given to illustrate this point.

The second point to be discussed is that the process of selecting the best material is accomplished by first finding the best combination of material and geometry. The reason for this is that, for a given load-carrying job, each different material may have a different "best" configuration, and the materials must be compared on the basis of the best they can do.

The third item to be discussed is one of the knottiest problems in design--the problem of multiple strength requirements. Many structural components have several possible modes of failures and, in addition, are subjected to a variety of loading and environmental conditions. This means that the component must be designed to resist all of the possible failure modes that might occur under the variety of applied conditions. This situation will be referred to here as having "multiple strength requirements." For example, the wing structure of a Mach 3 transport must resist buckling failure, short-time ductile failure (yielding), creep failure, fatigue

failure, and others, under a variety of loading and elevated temperature conditions.

But before discussing minimum weight design further, there is an implied qualification that needs pointing out. Although we often discuss minimum weight as though it were a kind of absolute condition, we always have cost considerations enter in. We really never design anything for the absolute minimum of weight; rather, we reduce the weight down to a point where the cost of reducing it further exceeds the value of the weight saved. So in a sense, we really are designing for minimum cost--or at least we should be. However, it should be remembered that the minimum weight design methods that will be discussed are necessary steps in the process of achieving minimum cost design.

In flight vehicles the value of a pound of structure saved is usually quite high, and this is the reason that minimum weight and minimum cost tend to be equated in this application.

MATERIALS COMPARISON IN MINIMUM-WEIGHT DESIGN

One method that could be used to select the best material, from among a group of candidate materials, would be to design the entire piece of hardware in each material, and then choose the material giving the lightest design. Since this method would be impractical for a structure as complicated as an airplane wing, for example, a simpler approach is used; materials are compared initially on the basis of typical components that comprise the wing.

For example, a typical component of importance is the sheet-stiffener panel performing as a wide column. This component, which is generally designed by compression buckling considerations, comprises much of the structure one sees when he looks out the window of an airliner at the top surface of the wing. The design function of this component is to transmit a distributed load q lb/in through a distance L, as illustrated in Fig. 1. This is the structural job performed by a significant proportion of existing structures, ranging from applications in buildings and civil structures, to ground and flight vehicles.

There is a great variety of geometrical configurations that will perform the structural job illustrated. Because the topic of discussion is directed toward minimum weight, the configuration used for the example to follow will be a sheet-stiffener panel that is typical of aircraft construction.

The first step in the material selection process is a comparison of the efficiencies of the candidate materials as a function of the structural design job.

In order to make the comparison, the correct parameters must be determined for describing the job and for measuring efficiency. In some cases the parameters are fairly obvious (as in simple tension), and in others the parameters are somewhat more complicated, as will be discussed.

Before proceeding with the example, it should be pointed out that minimum weight design methods do not determine directly the lightest structure to perform a given job. What they do is to determine the least-weight

configuration of a specified generic family; for example, they can determine the lightest sheet-stiffener panel using square-hat-shaped stiffeners, or the lightest panel using some other shape of stiffener. So it is necessary to compare not only various candidate materials, but also various candidate geometries in order to determine the minimum-weight structure.

It should be noted, therefore, that minimum-weight design methods have by no means eliminated the need for skill and creativity on the part of the designer.

To continue with the example, the designer knows, or can determine, values of q and L (see Fig. 1) before he begins the design. He now wants to determine the combination of material and geometry that will result in the minimum-weight sheet-stiffener panel that will transmit the load q over the distance L.

Since this paper is directed toward material selection, the comparison will be limited to two generic families of geometry--the square-hat stiffener and the T-stiffener. Within each family, as mentioned previously, the elements of the sheet-stiffener panel must be proportioned so that the material is working most efficiently for each value of structural job (q and L).

The weight-efficiency parameter in this case is simple because the component has a constant cross section and a uniform stress; for a specified q and L the efficiency can be measured by the ratio stress/density.*

Although the detailed derivation of the proper job parameter for this structural element is outside the scope of this paper, it can be stated that

*It should not be concluded that higher stress always means higher weight efficiency, because there are applications, such as bending, wherein this is not the case.

in any case where we can write an equation that predicts failure (in terms of geometry and material properties), we can derive the proper structural job parameter. For example, the failure of a sheet-stiffener panel in the over-all buckling mode can be predicted by the Euler-Engesser column equation given in Eq. (1) as

$$\sigma = \frac{\pi^2 E_t \rho^2}{L^2} \tag{1}$$

where σ = buckling stress

E_t = tangent modulus

ρ = radius of gyration

L - effective hinged-end length

This equation is an analysis equation because it predicts the buckling stress for a column that has already been designed. (The factor ρ is not known until the geometry and size are specified).

However, since the designer does not know the geometry and size of the panel--this is what he is solving for--he cannot use Eq. (1) for design unless he resorts to a cut-and-try procedure. To solve the designer's problem, Eq. (1) is transformed into a design equation, as given by Eq. (2).

$$\sigma = \left[\pi^2 E_t K_\rho^2 \left(\frac{q}{L}\right)^2\right]^{1/3} \tag{2}$$

where σ = the maximum attainable buckling stress

K_ρ = a non-dimensional shape factor that the designer can specify

q/L = structural job parameter.

The inputs to Eq. (2) are all quantities the designer knows or can specify to begin with (material characteristics, general cross-section shape, and structural job) and the quantity solved for, σ, tells the designer how much material is required to perform the structural job.

If the example element had been a narrow column, a beam, or a shear panel, the procedure would still be essentially the same, although the job and efficiency parameters would be somewhat different.

Because of their current interest as possible candidates for the supersonic transport airplane, the materials chosen for the first example comparison are titanium 8-1-1 alloy and AM 355 stainless steel.

Figure 2 shows the compression stress-strain curves that were used in the design of the example sheet-stiffener panels to follow, and includes both room-temperature properties and short-time properties at 600°F. (The temperature 600°F corresponds approximately to Mach 3 flight.)

Figures 3 and 4 represent the minimum-weight design of sheet-stiffener panels using the materials of Fig. 2 for room temperature and 600°F. These figures show weight efficiency versus structural design job for sheet-stiffener panels using square-hat and T-shaped stiffeners. Weight-efficiency is measured by the stress/density ratio σ/w, where w is the density of the material and σ is the maximum stress that can be obtained for any value of structural job q/L.

It can be seen from Figs. 3 and 4 that the relative efficiencies of the steel and titanium alloys vary, depending on the magnitude of the structural job q/L, and depending on the temperature. This emphasizes the need

to base materials comparison and selection on a design method that will properly account for such variations. In some cases the relative efficiencies actually reverse with variations in structural job, as will be shown in the example to follow.

EXAMPLE OF IMPROPER COMPARISON OF MATERIALS

Misleading results can be obtained when improper comparison parameters are used, or when the geometry is not tailored to make the best use of each material being compared. To show an example of this, let us assume that we want to compare two materials for use in narrow columns. Let us further assume that the column cross section being considered is a square tube and that the two materials are F5-1H magnesium alloy and 7075-T6 aluminum alloy.

As a basis for the first part of the example, assume a pinned-end magnesium column 50 inches long that has a buckling load of 2500 pounds. This column will have a wall thickness of 0.0346 inches and a width of 1.63 inches, which are optimum values for this column.

Next, an aluminum column is designed to have the same weight, length, and cross-section proportions. The failure load for this equal-weight aluminum column is only 1730 pounds.

Since the magnesium column is 1.44 times as strong as the aluminum column, one might be tempted to conclude that the magnesium is 1.44 times as efficient, on a weight basis, as the aluminum. However, this would be an erroneous conclusion for two reasons, as the rest of the example will show.

The first error in the comparison is that of making the geometric proportions of the aluminum column the same as those of the magnesium column,

whereas the best aluminum column will have different proportions from the magnesium. When this error is corrected the ratio of magnesium/aluminum strength decreases from 1.44 to 1.28. These comparisons are shown in the first three bars of Fig. 5.

A further error in the comparison is that the wrong parameter is being used as a basis of comparing efficiencies--that of strength. The designer does not want to maximize strength--he wants to minimize weight. He knows the required strength to start with; therefore he wants to compare weights for a given strength or structural job*--not vice versa. The comparison of weight will be different from the comparison of strength.

To continue the example, if an optimum aluminum column is designed to have the same strength as the magnesium column, the ratio of aluminum weight to magnesium weight is 1.13, as illustrated in Fig. 5. This indicates a smaller difference between the efficiencies of the two materials than the comparison of strength for equal weight.

To illustrate further how the comparison depends on the proper specification of the design job, if the structural job is changed from $P/L^2 = 1.0$ psi to $P/L^2 = 100$ psi, we find that the relative efficiencies have reversed--the optimum magnesium column is now more than twice as heavy as the optimum aluminum column, as shown by the right-hand pair of bars in Fig. 5.

MULTIPLE STRENGTH REQUIREMENTS

The preceding examples were designed on the basis of a single applied loading condition and a single failure mode. However, in actual hardware design the situation is seldom this simple. The designer is usually faced with the

*For a narrow column the structural job is measured by P/L^2, where P is the design load and L is the effective pinned-end length over which the load is transmitted.

more complicated problem of designing a hardware component to withstand a multiplicity of loading conditions, environmental conditions, and failure modes. In this complex situation the minimum weight design methods, based on a single requirement, cannot do the complete job. However, they do play a vital role in providing the first step in the design process, including selection of materials.

The procedure generally followed is to select an initial menu of candidate materials and then compare their efficiencies in performing what appears to be the most critical single job required of the types of structural components involved in the hardware being designed. At this point some of the materials would probably be eliminated.

In addition to this, the candidate materials are also screened according to other factors, including mechanical behavior characteristics, fabricability, metallurgical stability, etc., as appropriate to the design application. For example, a candidate material might be eliminated on the basis of brittle behavior in tension.

After the menu of materials has been narrowed down to a few most likely contenders, further evaluation will probably necessitate use of a specific design application. The reason for this is that a given application will require different magnitudes of the various kinds of strength. Since a material provides a unique combination of strength values, for the various types of strength required, the material may have to be compared against the specific application to see how well it meets all of the strength requirements.

An initial design and sizing of the structure would be based on what appears to be the most critical loading condition and the most critical failure mode. Then the resulting structure would be analyzed to see if it meets the other strength requirements.

As an example, let us consider the design of the wing structure for a transport airplane. In the past, the major portion of a wing structure was designed on the basis of static strength--the resistance to short-time loading imposed on the aircraft by maneuvers or gusts. One requirement specified that the inelastic strain in the structural material should not exceed 0.002 inches/inch at the greatest load the aircraft was expected to experience. It was further required that the structure should not break until this greatest expected load was exceeded by 50%.

When these two requirements were met, the resulting design usually was more than adequate with regard to other strength requirements. For example, a list of major strength requirements, or resistances to failure, might include the following:*

1. Resistance to buckling failure
2. Resistance to yielding (permanent deformation)
3. Resistance to ductile tensile failure
4. Resistance to fatigue
5. Resistance to brittle tensile failure
6. Resistance to creep

*This is not intended to be an all-inclusive list, nor are all of the various failure modes mutually independent.

The static strength requirements, which correspond generally to Items 1, 2, and 3 usually provided ample resistance to failure in the other modes, such as fatigue and brittle failure in tension.

However, as structural alloys were improved to provide greater resistance to the first three failure modes, the resistance to the other failure modes seldom increased proportionately. Because of this, and because the applied stresses were increased, new failure modes--such as fatigue--became more critical.

In addition to changes in materials, the applied operating conditions also changed. For example, the higher operating altitudes of pressurized jet transports brought about an increased concern for the behavior of materaisl and structures subjected to biaxial tension. Further, the advent of supersonic speeds has introduced the consideration of elevated-temperature effects, such as creep, in design of the wing structure.

It can be seen that when increased performance is asked from the hardware being designed, the critical strength requirements tend to increase both in number and in magnitude. This in turn complicates the design, including the selection of materials.

For example, the design of the structure for a Mach 3 transport will have to consider all of the strength requirement items above, as well as their possible interactions.

In the event that the analysis of the initial design detects inadequacies in strength for any of the alternate design conditions being checked, the strength of structure would then be increased by the required amount at the necessary portions of the structure.

Unless the design or the operating conditions are radically new, experience will generally provide the basis for anticipating which design conditions are the most critical, and therefore the changes indicated by the analysis might be small. In this situation probably no significant changes would be made in the design, other than making an existing part slightly different.

When a component must be altered from its original design, in order to make it adequate for other design conditions, there exists the theoretical possibility of optimizing the design with respect to both design conditions simultaneously. However, unless the change is a major one, the simultaneous-optimization game is seldom worth the economic candle, and the existing part would simply be "beefed up" as required.

PROBLEM AREAS IN DESIGN OF ADVANCED HARDWARE

To provide a basis for the design of structures and the selection of materials there are three kinds of information required:

1. Knowledge of the relationships for predicting structural behavior and conditions of failure in all of the modes relevant to the design.

2. Knowledge of material behavior characteristics that are needed for use in the relationships that predict structural behavior and failure.

3. Knowledge of the applied conditions, such as loading history and environment, to which the hardware will be subjected.

When the hardware is of a new or advanced type, the designer is often hampered initially by a lack of adequate information in one or more of these

three areas. In this situation the problem of design and materials selection is more difficult, costly, and uncertain.

In recent years our technological advancement has created an increasing number of these situations--particularly in the area of flight vehicles--wherein the design had to be commenced without complete information in the three areas. And the premium that flight vehicles place on minimizing weight is a chief contribution to the difficulty of the problem.

For example, the increased emphasis on light-weight design of pressure vessels--for use in rocket boosters and high-altitude pressure cabins--has required new information on the behavior of materials and structures under biaxial tension, which is the type of information referred to in Items 1 and 2.

The increased operating temperatures of flight hardware has required a great deal of new information about material characteristics (Item 2).

Designing hardware to operate in the space environment, for example, has introduced the need for a great deal of new information about applied operating conditions (Item 3).

The structure of a Mach 3 transport represents an example of an advanced type of hardware, having complex multiple-strength requirements, for which the designer currently does not have all of the necessary information of the three kinds mentioned above. This example will be discussed next.

SUPERSONIC TRANSPORT

The design of the structure for a Mach 3 aircraft has much in common with the design of subsonic aircraft structures. However, the addition of

elevated-temperature (nominally about 600°F) to the operating environment has greatly complicated the problem because it introduces not one but two new parameters to be accounted for--temperature and time.

In the design of subsonic aircraft there have been no time-dependent behavior modes of major significance to the structure. Since fatigue behavior in subsonic aircraft depends on the number of stress cycles, rather than time per se, equivalent operating time can be compressed in fatigue tests by rapid cycling.

However, elevated-temperature introduces the possibility of time-dependent behavior such as creep, metallurgical changes, and can introduce time effects into fatigue behavior. This means that until valid analytical relationships can be derived for predicting temperature/time effects, there will be a great deal of time and expense required in obtaining design information from full-time tests. The design lifetime for a supersonic transport is expected to be in the range of 30-50,000 hours; a 30,000 hour data point takes approximately 3-1/2 years to obtain in actual time.

Since full-time tests will undoubtedly have to be made, if only to support development of analytical relationships, this puts a premium on prompt initiation of relevant tests.

As in subsonic aircraft, the static-strength requirements of the Mach 3 aircraft appear to represent the conditions critical to most of the structural design (although these strength conditions must include the effect of elevated temperature on the material). The initial screening of materials can then be done on the basis of weight-efficiency factors

derived from minimum weight design theory, such as illustrated in Fig. 4. In addition to this, the materials would be screened further according to other types of behavior, as discussed below.

Figure 4 compares steel and titanium on the basis of buckling strength, which is determined by the compression behavior of the material. However, other portions of the structure are designed primarily by tension loading, and because of reversed loading nearly all of the structure is subjected to tension at some time. Therefore the structure must have tensile strength to resist failures such as tensile yielding, fatigue, brittle behavior such as rapid crack propagation, etc. It is in the area of tensile failure that there exists the greatest need for the development of methods for predicting behavior.

The resistance of a material to brittle-type failure is approximately determined by several tests, such as tensile tests of notched specimens, cracked specimens, and by tests that measure elongation and reduction in area at failure. Behavior of material under conditions of biaxial tension is studied by means of bend tests and tests of miniature pressure vessels.

There is disagreement as to the validity and interpretation of the various tests. However, until valid analytical methods are developed, the materials selection and design will continue to be based largely on such tests.

In addition to analysis for resistance to brittle failure, the initial design must also be analyzed for creep and fatigue. Considerable effort to improve methods of analysis are currently under way, particularly for fatigue.

Analysis is complicated by the fact that cumulative damage rates in both creep and fatigue are stress dependent, and in most flight vehicle structures the stress is varying.

In summary, then, it can be seen that the materials selection process, even for complex multiple strength applications, proceeds on the same basis as for the simpler design conditions. A menu of candidate materials is selected and rated on the basis of structural weight efficiency, and then other requirement criteria are applied in a subsequent process of elimination.

COST

In conclusion, I would like to reiterate something mentioned earlier--that although in some applications minimum weight may appear to be synonymous with minimum cost, this really is not the case--at least not in the absolute sense. In every application where weight is important, including such applications as trucks, aircraft, and bridges, there exists a value for a pound of weight eliminated. We would eliminate any weight that could be eliminated at a cost that is less than the value of the weight saved.

Ideally, we would like to design the structure on the basis of minimum cost rather than minimum weight. However, the cost that should be minimized is not the cost of the structure but rather the total cost of the hardware system, including such costs as development, production and operating costs. The great difficulty here is the problem of determining the cost inputs necessary to such a computation. At the present time the cost factors for advanced flight vehicles cannot be predicted nearly as accurately as can the vehicle performance. (It is recognized, however, that in other areas of structural

design, such as civil and architectural structures, costs may be estimated with greater confidence.)

However, there are continuing efforts to include cost considerations in the earlier stages of design of flight vehicles, and some progress is being made in this direction; eventually perhaps we can learn how to design advanced hardware for minimum cost. Even so, as discussed earlier, minimum weight design methods will still represent an integral part of the process.

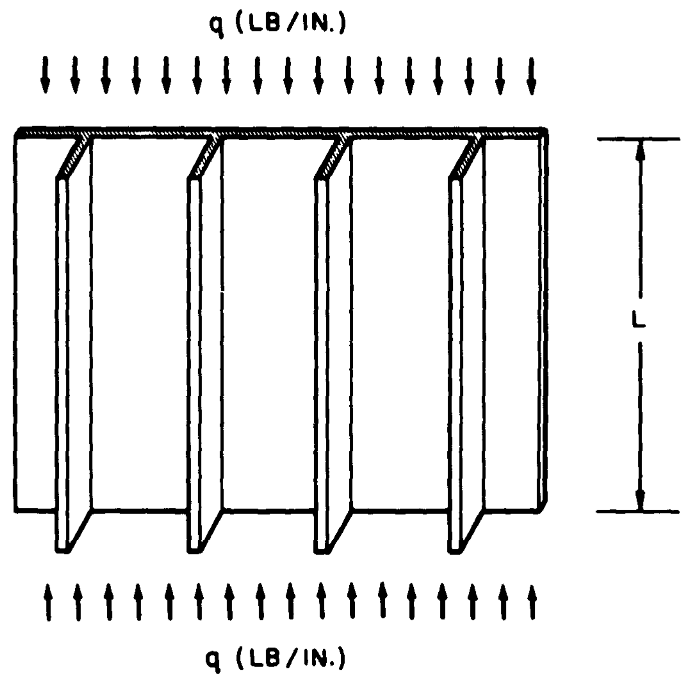

Fig. 1—Structural job for wide-column element

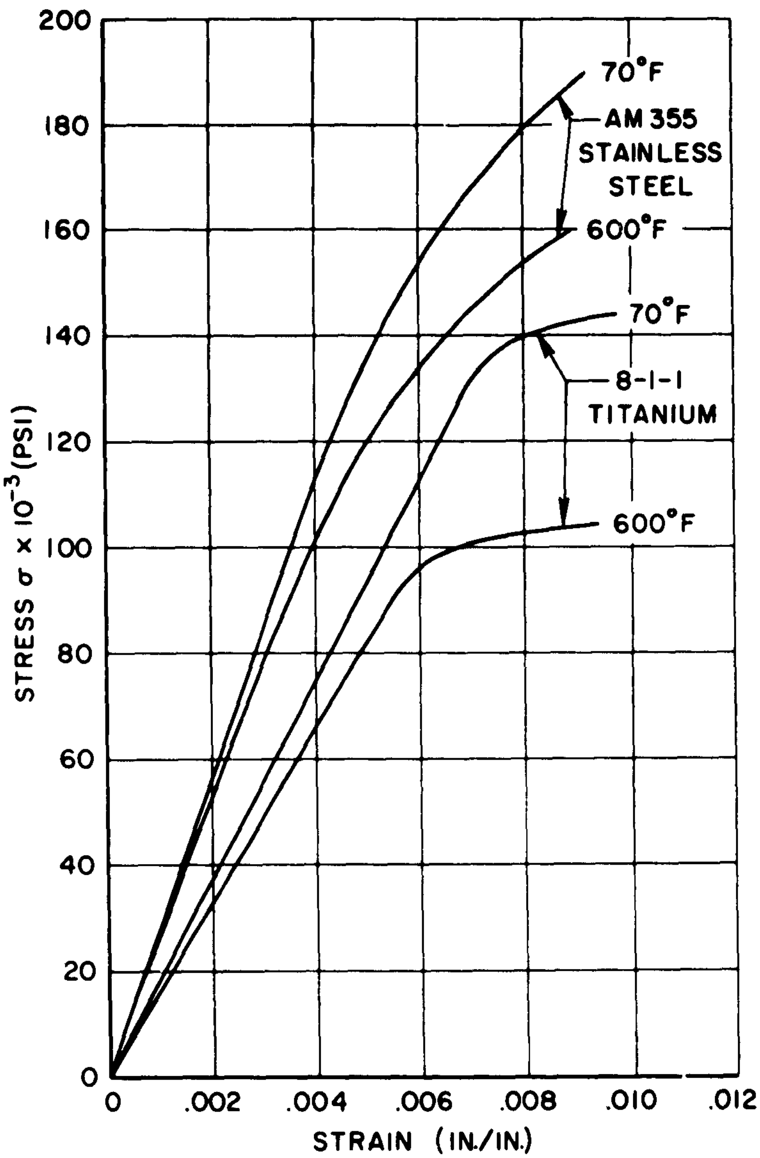

Fig.2—Typical compression stress-strain curves for example materials

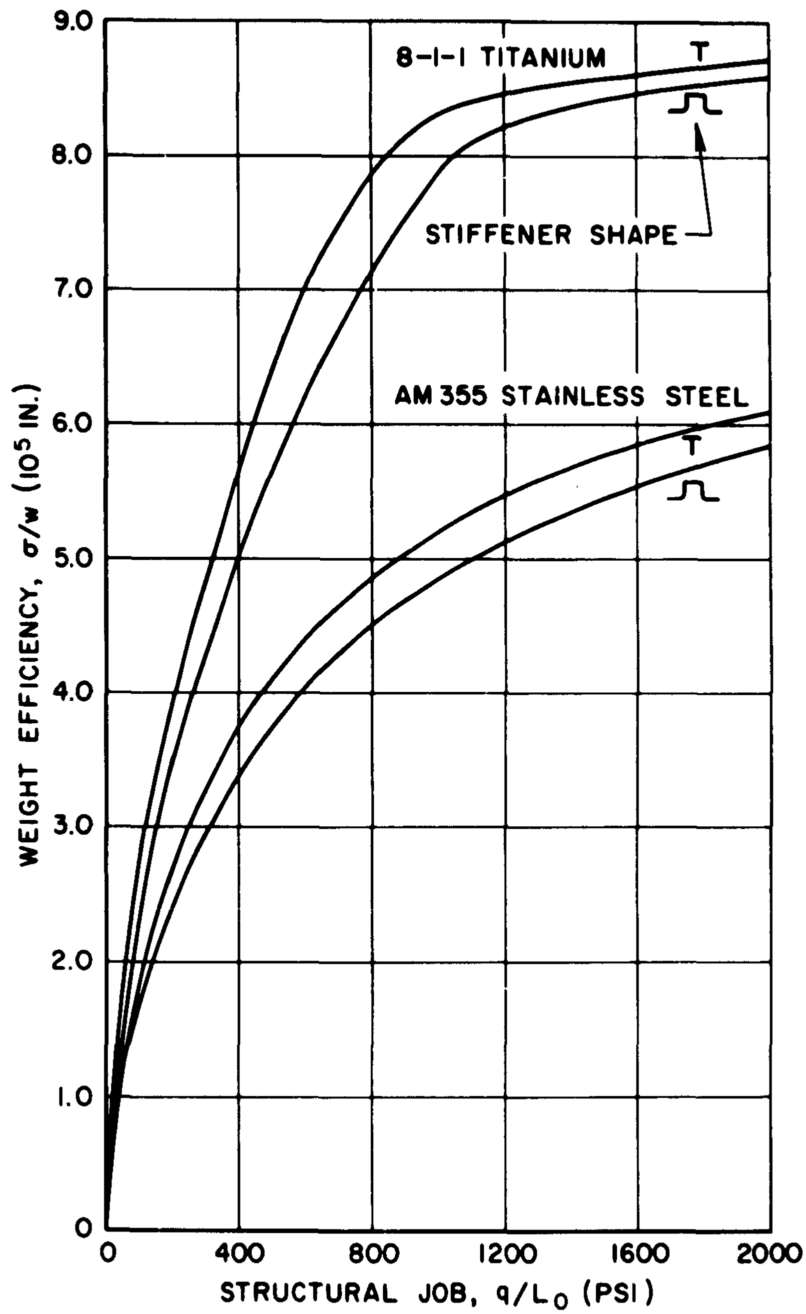

Fig. 3—Variation in weight efficiency for sheet-stiffener panels at room temperature

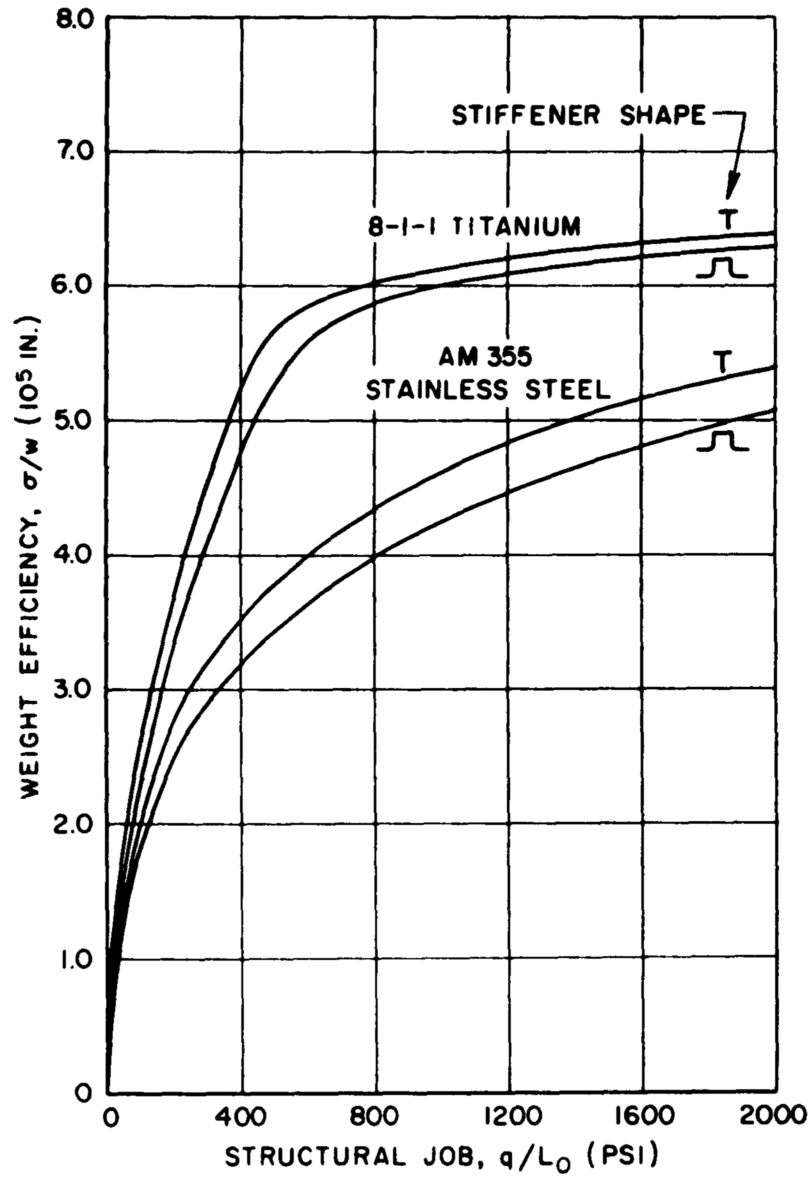

Fig. 4 — Variation in weight efficiency for sheet-stiffener panels at 600°F

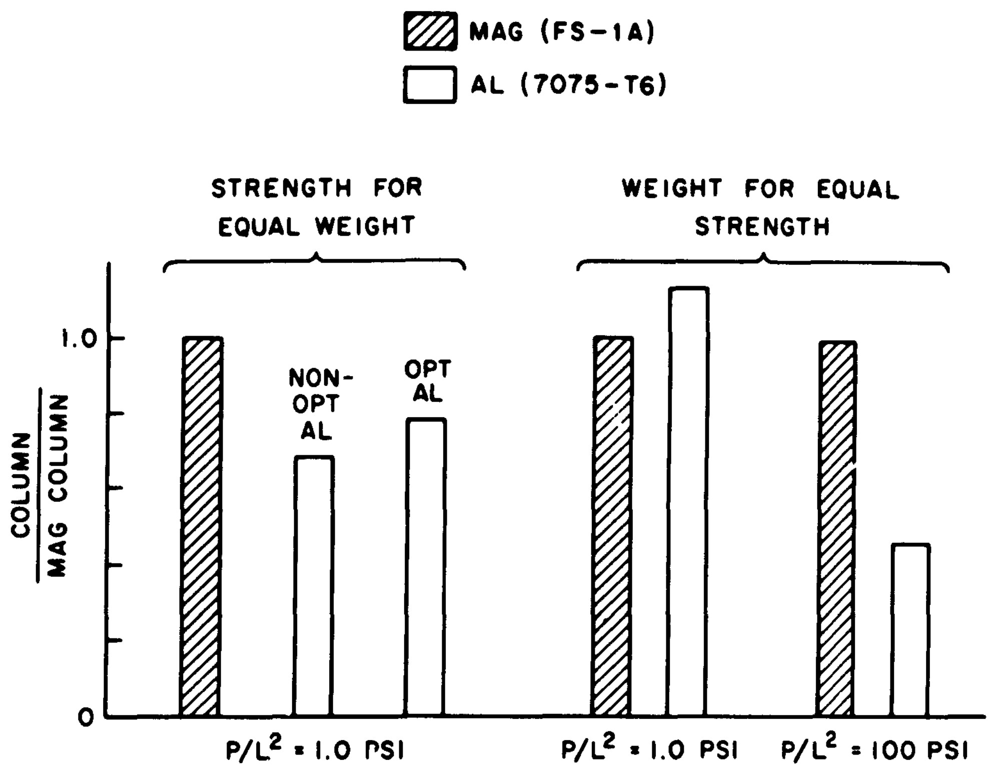

Fig. 5—Comparison of relative efficiency of magnesium and aluminum in columns